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Between- and within-subject variance of motor variability metrics in females performing repetitive upper-extremity precision work

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ABSTRACT

Kinematic motor variability is extensively studied in occupational, clinical and sports biomechanics, but the consistency of most motor variability metrics have never been reported. In this study, fourteen subjects performed a repetitive pipetting task on three separate days. Movements of hand, arm and pipette tip were recorded in 3D and used to compute shoulder elevation, elbow flexion and shoulder-arm coordination angles, as well as pipette-tip endpoint precision. Cycle-to-cycle motor variability was quantified using linear dispersion measures of standard kinematics properties such as peak velocity, range of motion, and inter-segmental relative phase. Between- and within-subject consistencies of these variability metrics were quantified by variance components estimated using a nested random effects model. For most metrics, the variance between subjects was larger than that between days and cycles. Entering the variance components in statistical power equations showed that for most metrics, a total of 80–100 subjects will be required to detect a 20% difference between two groups with sufficient power, while this difference can typically be detected in repeated-measures (paired) designs using 25 subjects. The reported between and within-subject variance components can be used as a data base to facilitate efficient designs of future studies of kinematic motor variability.

1. Introduction

Motor variability (MV) refers to the intrinsic variability naturally present in the motor control system. Occurring even in the simplest movements, it is usually manifested as a difference in joint movements, joint coordination and/or muscle activities between successive repeats of a task, even when the individual tries to identically repeat that task. Contrary to the traditional view that MV is just noise that is detrimental to performance, it is now widely accepted that increased MV may not lead to deterioration in performance (Newell and Slifkin, 1998; Slifkin and Newell, 1998; van Emmerik and van Wegen, 2002), and that MV may actually have an important functional role in skill acquisition and prevention of overuse injuries (Arutyunyan et al., 1969; Hamill and van Emmerick, 2000; van Emmerik and van Wegen, 2000; Riley and Turvey, 2002; Mathiassen, 2006; Madeleine, 2010).

An interest in MV has emerged in occupational research due to its associations with pain/discomfort, fatigue and performance (Srinivasan and Mathiassen, 2012); in a clinical context focusing on pain, aging and diseases (Heiderscheit, 2000; van Emmerik and van Wegen, 2000) and rehabilitation (Field-Fote and Tepavac, 2002; Daly et al., 2007); and in sports biomechanics because MV is associated with performance and injury risk (Davids et al., 2003; Glazier et al., 2003; Bartlett et al., 2007; Preatoni et al., 2013).

Studies of kinematic MV have used a variety of metrics, which fall into four classes (Srinivasan and Mathiassen, 2012): (1) metrics treating variability as statistical dispersion, such as cycle-to-cycle standard deviations, (2) metrics based in chaos theory and non-linear dynamical systems models such as entropies and Lyapunov exponents, (3) metrics assessing coordination variability, such as cross-correlations and inter-segmental relative phase and (4) metrics viewing variability as a consequence of redundant degrees of freedom, such as the Uncontrolled manifold hypothesis.

Although an abundance of MV studies have been conducted for different purposes, using the large array of metrics outlined above, the sources and sizes of variance within and between subjects of any particular MV metric is not well understood. Information about these statistical properties is needed to properly design studies with sufficient statistical power to investigate associations

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between suspected risk factors and relevant outcomes in epidemiology, to identify differences in MV between groups of, for instance, different age or proficiency, pain and no-pain populations, and to assess the effect of interventions on individuals, like medical treatment or motor training. Some studies in the gait literature do, indeed, discuss how many steps are needed to be measured to reliably estimate stride variability characteristics (Owings and Grabiner, 2003; Hollman et al., 2010), but these studies only focus on within-day variance in MV, and do not discuss the size of between-days or between-subjects variance.

In this context, we performed a study to estimate the sizes of between- and within-subject variance of kinematic motor variability measured using motion-tracking systems in healthy females performing repetitive cyclic precision work. We also interpreted these variances in terms of the number of subjects required to obtain sufficient power in studies of motor variability conducted as unpaired designs comparing groups; and as paired designs comparing conditions repeated on different days using subjects as their own controls. In this paper, we address motor variability metrics belonging to the 'dispersion' and 'coordination' classes described above, as well as some metrics addressing variability in the endpoint of the kinematic chain, with implications to motor performance.

2. Methods

Pipetting was used to model repetitive precision work using the upper extremities (Park and Buchholz, 2013). The pipetting task (below) was performed in the laboratory by 14 healthy female subjects, aged 20–45 years and experienced in pipetting, on 3 different days under identical conditions. All subjects were right-handed, and free from any shoulder pain or injury. All subjects signed an informed consent and the experiment was approved by the Ethical Review Board in Uppsala, Sweden.

2.1. Workstation-setup

One pipetting cycle consisted of aspirating water from a big pickup-tube, transferring it to one of eight small target tubes in a 10×10 array of identical tubes, and returning to the pickup-tube (Fig. 1). Light emitting diodes mounted below each tube were used to indicate when and to which target-tube liquid was to be transferred in each cycle, as controlled by custom-made software. The participants sat in a rigid chair, and trunk movements were restricted by fixing their torso to the back of the chair by belts. The table surface was height-adjusted such that the participants' lower arms would be horizontal when they sat upright on the chair, with arms relaxing on the table.

2.2. Repetitive work-task

One pipetting session consisted of transferring liquid to each of the eight target-tubes 20 times in a randomized order, i.e. in total

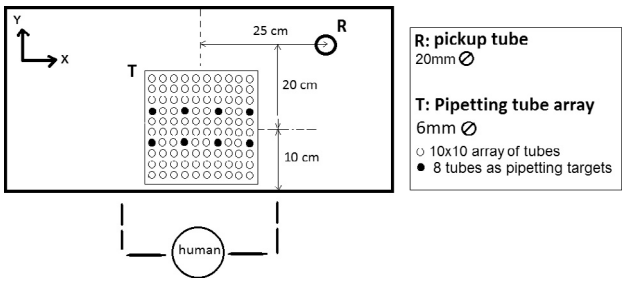

Fig. 1. Workstation set-up.

160 cycles, at a standard work pace of 2.8 s/cycle. The entire session could be performed without any significant localized muscle fatigue in the arm, as confirmed by a stable frequency content of electromyographic signals from the upper trapezius and forearm extensor muscles throughout the session (Cifrek et al., 2009). In order to get acclimatized to the setup, on all test occasions, participants performed 100 pipetting cycles before actual data collection.

2.3. Data collection

Kinematic data were recorded by means of two synchronized electromagnetic tracking systems (Fastrak, Polhemus, USA), at a sampling rate of 30 Hz. Six degrees-of-freedom sensors were firmly placed on the skin on the following locations: the right shoulder on top of the acromion; the dorsal surface of the upper arm, approximately 5 cm from the elbow joint; the dorsal surface of the forearm, approximately 2 cm from the wrist joint; on the back of the hand, centered between the wrist joint and the meta-carpophalangeal joint of the middle finger; and on the pipette, about 5 cm from the pipette-tip. A three-segment rigid-body model of the upper arm, forearm and hand segments (described in Domkin et al., 2005), was used for estimating the shoulder, elbow and wrist joint angles as defined by the ISB conventions (Wu et al., 2005). Thumb forces were recorded using a thin-film finger-tip force sensor (A201, Tekscan Inc., USA) mounted on the pipette's push button. In addition, electromyography recordings were collected from shoulder and arm muscles but only the kinematics data will be presented in this paper.

2.4. Data processing

Kinematic data were filtered using a fourth order, low-pass Butterworth filter with a cutoff frequency of 3 Hz. Only the transfer part of each cycle, i.e. when liquid was transferred from the pickup-tube to a specific target-tube, was used for further analysis. For each cycle, the start point was defined as the time instant when the pipette tip was at the pickup-tube and its velocity was at minimum; and the end point was defined as the instant when the force on the pipette's push button was maximum (to dispel liquid into the target tube). The time instants when the velocity of the pipette-tip increased above and decreased below 5% of peak velocity were used as cut-off points to further trim each cycle. This procedure resulted in 20 processed cycles of shoulder, elbow and wrist joint angles and pipette-tip trajectories to each target (Fig. 2). The pipette-tip trajectories and shoulder elevation and elbow flexion angles were used for further analysis (illustrated in Fig. 3).

2.5. Data analysis

For each cycle of pipetting, cycle time was registered in seconds. In addition, the kinematic variables listed in Table 1a, indicative of motor performance, were computed for pipette-tip trajectories; kinematic variables listed in Table 1b were computed to describe shoulder elevation and elbow flexion movements; and the kinematic variables listed in Table 1c were computed to quantify shoulder–elbow coordination.

2.6. Cycle-to-cycle variability

For cycle time as well as each variable listed in Tables 1a–1c, cycle-to-cycle standard deviation was calculated across all 20 cycles to each target as an operational measure of motor variability. For time-normalized variables, i.e. (B9), (B10) and (C4), variances were first calculated at each time point of all cycles, the values from all time points were then averaged and the square